ULTRASONIC AMPLITUDE AND TIME MEASUREMENTS IN GAS IDENTIFICATION

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Abstract: This paper describes work which has been undertaken to identify individual gases and gas mixtures employing techniques which are based solely on ultrasonic means. The method employs broad-band capacitive ultrasonic transducers to measure the transmission of ultrasound over a wide range of frequencies across the gas or gas mixture under investigation. The results can be used to infer the composition of the gas and thus estimate such properties such as the density or calorific value of the gas or gas mixtures. The relevance of this work is mainly in its use in the gas distribution and transmission system where increasingly ultrasonic flow measurements are being employed and where an additional ultrasonic measurement would convert the volumetric flowmeter into an energy meter.

Keywords: Gas identification, ultrasonic methods, capacitive transducers, energy metering

1. INTRODUCTION

The work in this paper describes work which has been undertaken into the development of a system which is capable of identifying individual gases and gas mixtures using only ultrasonic means. The methods developed to date involve using broad-band capacitive ultrasonic transducers to measure the transmission across a sample of the gas over a wide range of frequencies and to use the results obtained to identify the composition of the gas and thus obtain such properties as the density or calorific value of the gas or gas mixture. The methods used for identification have involved amplitude and time measurements which are described in this paper and frequency domain methods which are described in the paper by Hemp, Rawes and Sanderson [1].

The relevance of this work is mainly in the application of ultrasonic methods to measure the calorific value of fuels within the gas distribution and transmission system where increasing ultrasonic flow measurement technologies are being employed throughout the system from the high pressure transmission system [2], [3] to domestic metering [4], [5]. By adding the measurement of composition by the use of ultrasonic techniques it would be possible to convert volumetric or mass flowmeters into energy meters.

A typical gas composition with which such a system would have to deal with has been provided by British Gas [6] and is shown in Table 1.

Table 1: Compositional Ranges for Natural Gas in the UK

Component	Lower Limit %	Upper Limit %
Methane	84.0	98.0
Ethane	0.25	9.0
Propane	<0.01	3.5
i-Butane	0	1.0
Nitrogen	0.05	10.0
Carbon Dioxide	<0.01	5.0

The work has thus concentrated on the measurement of composition where Methane is the base gas and where other hydrocarbon gases are present at concentrations below 10%.

Given a known composition of the gas mixture, it is possible to compute the speed of sound from thermodynamic considerations [7] and methods are also available for measurement of the speed of sound to a very high degree of precision [8]. However, using only the speed of sound, other than for simple two component mixtures [9], it is not possible to infer composition simply from speed of sound measurements. Previous work in the Department of Process and Systems Engineering using swept frequency interrogation of gases demonstrated that additional information, regarding attenuation across the gas as a function of frequency, could be used as a means of identifying gas composition for Methane/Ethane mixtures [10]. This paper describes the use of broad-band pulse transmission methods to accomplish a similar task and the extension of the method to three component mixtures.

2.   CAPACITIVE ULTRASONIC TRANSDUCERS

One of the major difficulties which is encountered in the design of ultrasonic flowmeters for gas applications, particularly at low pressure, is the ability to design wide bandwidth, low Q, transducers for such applications. The high acoustic impedance of the piezoelectric material itself and of any matching layers relative to the acoustic impedance of the gas make the efficient transmission of ultrasound into the gas difficult. Ignoring the attenuation effects of the ultrasound in the gas it is not possible, using piezoelectric generation methods, to transmit a broad-band of frequencies using pulse excitation. However, by using capacitive transducers it is possible to achieve such a transmission.

2.1   Operation of Capacitive Ultrasonic Transducers

Capacitive transducers have been previously described in the literature by Carr [11], Carr and Wykes [12], Mohamed [10], Rafiq and Wykes [13] and Schindel and Hutchins [14], [15]. Figure 1 shows the basic construction of such capacitive transducers. The transducers typically consist of a roughened or grooved metallic backplate across which is stretched a thin Mylar film, typically with a thickness in the range 2.5μm to 5.0μm, the front surface of which has a thin aluminium metal coating. The capacitance thus consists of the two plates, the backplate and the front aluminium coating, and a dielectric consisting of the thin Mylar film and the gas filled gaps created by contact of the Mylar film with the peaks of the roughened surface or the tops of the grooves on the backplate.
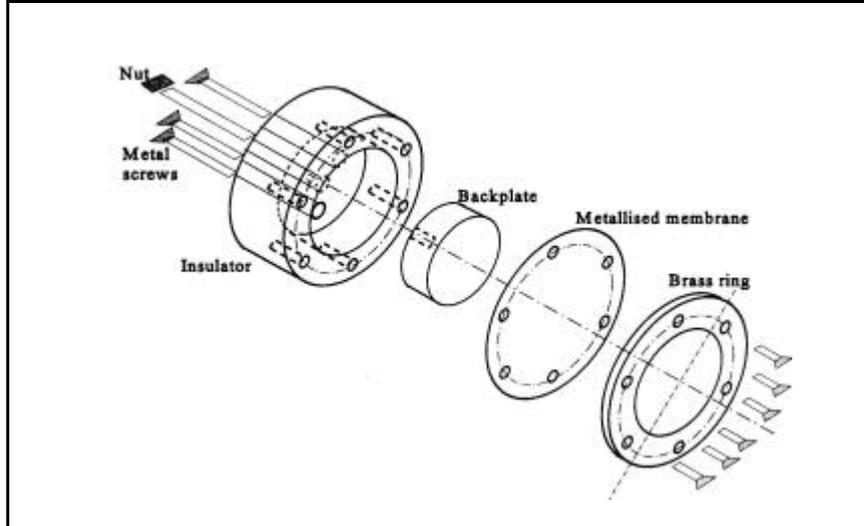

Figure 1: Capacitance Ultrasonic Transducers

Application of a dc voltage between the two plates of the capacitance creates a force on the membrane given by:

$$F = \frac{\varepsilon_0 . A . V_{dc}^{\ 2}}{2 . \left(d_a + \dfrac{d_m}{\varepsilon_m} \right)^2} \tag{1}$$

where F is the generated force, A is the area of the film, V_{dc} is the applied dc voltage, d_a is the effective thickness of the air gap, d_m is the thickness of the Mylar film, ε_0 is the permittivity of freespace, and ε_m is the permittivity of the Mylar film

On the application of an ac voltage V_{ac} in addition to the dc voltage the force becomes :-

$$F = \frac{\varepsilon_0.A.(V_{dc}^{\,2} + 2.V_{dc}.V_{ac} + V_{ac}^{\,2})}{2.\left(d_a + \dfrac{d_m}{\varepsilon_m}\right)^2} \tag{2}$$

and thus the membrane is subject to an ac force in addition to the dc force. The membrane and the gas trapped between the Mylar film act as a damped resonant system having a low Q. By suitable choice of membrane thickness and the dimensions of the roughness or grooves on the backplate it is possible to adjust the frequency range over which the transducer will operate. As a receiver the modulation of the capacitance by the applied pressure field results in a charge variation when a constant dc voltage is applied to the receiver which can be detected by means of a charge amplifier.

2.2   Transmitter/Receiver System and Data Logging

In the work described in this paper two separate capacitive transducers manufactured for us by Partec Research and Development of Canada have been used as the transmitter and the receiver. Although both of these transducers are capacitive transducers with micro-machined backplates, with an active area 10mm in diameter and a capacitance in the region of 600 pF, their performance as a transmitter/receiver is optimised by the choice of applied dc voltage. As a transmitter the manufacturer recommends a maximum applied voltage of both bias and pulse of less than 350V. We have operated the devices with a positive bias of 300V and a negative pulse of –250V peak. As a receiver the performance is optimised for a dc voltage of +100V. Figure 2 shows the method of applying the pulse to the transducer and detection of the received pulse. The pulse is generated using a Panametrics Model 500PR Ultrasonic Pulser/Receiver. This generates negative going pulses of either –125V with a rise time of 7ns or –250V with a rise time of 10ns. It has been found necessary to insert a charge detection stage between the transducer and the Model 500PR receiving electronics since its 500Ω input impedance causes attenuation at low frequencies. The output from the Panametrics 500PR is fed into a PICO ADC-200 data logger which logs data at a sampling rate of 10ns and which is interfaced to a DELL 333MHz PC for bulk storage of data.
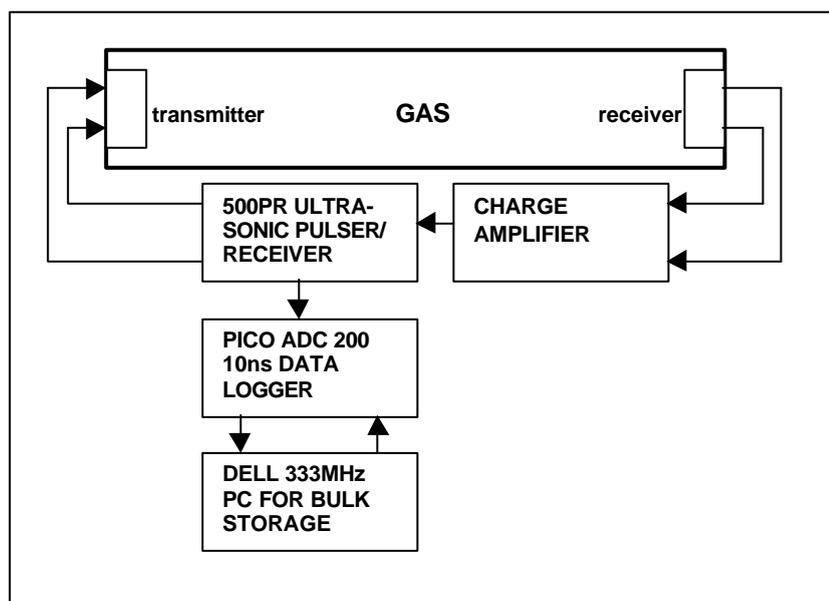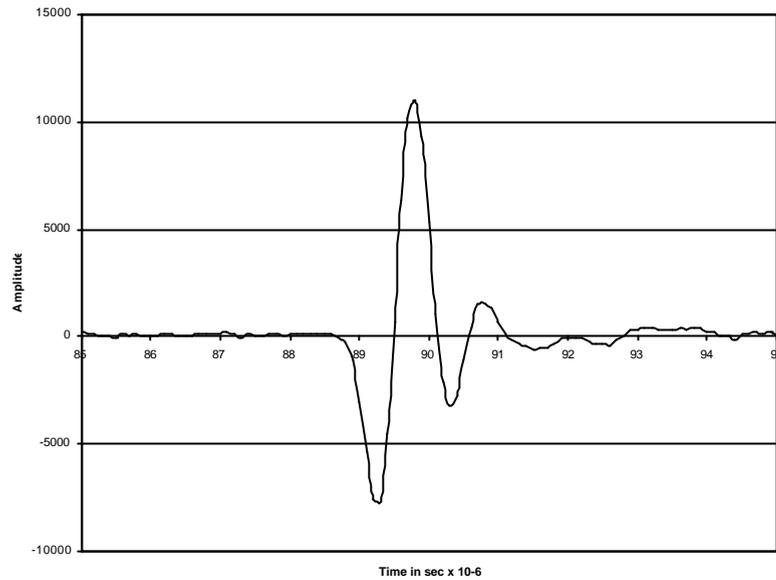

Figure 2: Transmitter/receiver system

Figure 3 shows a typical output trace obtained using the system. The response shown is to a 250V

–ve going pulse obtained from the PR500 ultrasonic pulser/receiver.

Figure 3 : Received signal for Pure Methane for 30mm transmitter/receiver separation

Figure 4 shows the spectral response of Methane. The spectral response shows that using this method it is possible to effectively transmit signals across the Methane from 50 kHz to 1.4MHz.
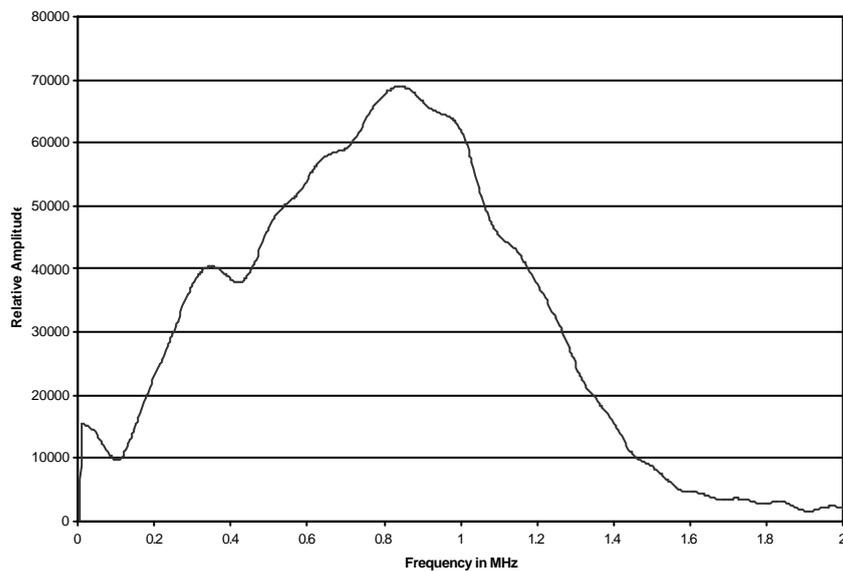

Figure 4: Spectral response for methane

3.   RIG CONSTRUCTION AND EXPERIMENTS

A rig has been designed and constructed which operates at atmospheric pressure and operates in an environment in which the temperature is typically controlled to $\pm0.5°C$. The separation between the transmitter and receiver can be adjusted from 0 to 200mm. However, in most of the tests undertaken on Methane based gases the separation has typically been in the range of 30mm to 150mm. An extensive range of experiments has been undertaken on the rig to collect data from a range of gas mixtures including pure Methane, Methane/Ethane mixtures in the range 99%/1% by volume to 94%/6% by volume and Methane/Ethane/Propane mixtures in the range 95%/4%/1% to 92%/6%/2%.

The gases were provided pre-mixed by BOC and their composition certified. For each of the tests the stored data consisted of the time response and transit from transmission to the first negative zero crossing of the response.

4.   ANALYSIS OF RESULTS

A series of analyses were undertaken on the data to identify measurements which could be used to distinguish the gas composition. These include time domain data sets based on the transit time and parameters of the received pulse shape; and frequency based analyses including the peak on the spectral response and the bandwidth of the response curve. Of these the most consistent was that based on mapping the amplitude of response, measured as the peak to peak value between the first negative going peak and the first positive going peak against the transit time, as shown in Figure 5 below.
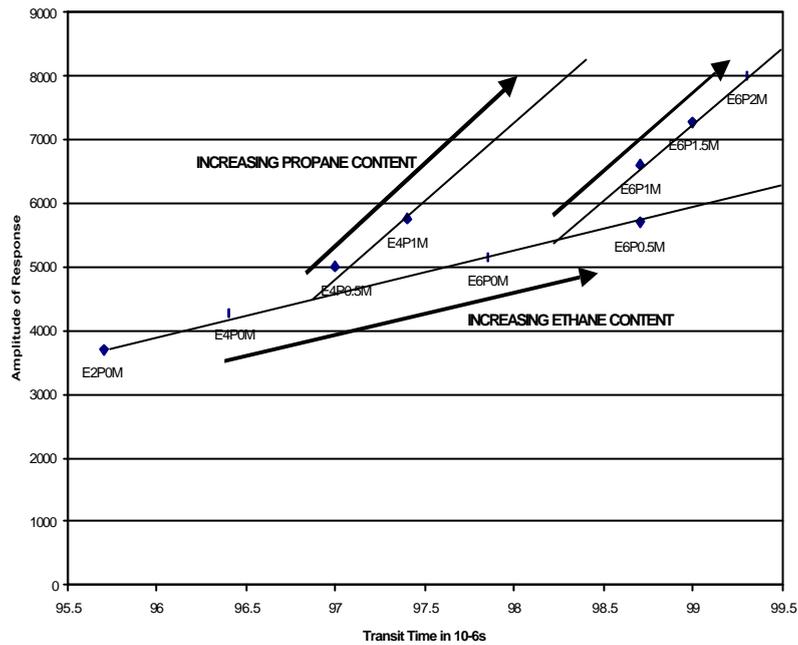

Figure 5: Amplitude of Response versus transit time for various gas mixtures

These results show that the addition of Ethane to Methane provides a linear shift on the amplitude/transit time map whilst the addition of Propane to the Methane/Ethane mixtures leads to a series of linear bifurcations from the Methane/Ethane line. Thus, there is a unique mapping for any given Methane/Ethane/Propane mixture on this amplitude/transit time map. From the results obtained the proportion by volume of each of the constituent gases can be determined by approximately ±0.5%. Once the composition has been determined then it is a relatively straightforward matter to determine either calorific value, density or both. The changes which have been measured are well within fairly straightforward measurement methods. In particular the change in amplitude for small changes in composition is much larger than any change which could be explained by a change in the density of the gas. It has therefore been necessary to construct an explanation of significant amplitude changes which have been observed. This explanation is given in the next section.

5.   RELAXATION EFFECTS IN METHANE

As has been shown by Trusler and Zarari [8], in addition to the classical attenuation which occurs in Methane there is a relaxation effect which at NTP occurs at a frequency of 97kHz. This can be modelled by a single relaxation time and gives rise to an attenuation α, additional to the classical attenuation :-

$$\alpha = \frac{\omega}{4.c_0} \cdot \frac{(\gamma_0 - 1)^2}{\gamma_0} \cdot \frac{\omega.\tau.F}{1 + (\omega.\tau)^2} \tag{3}$$

where c_0 and Υ_0 are the speed of sound and the ratio of the specific heats of the gas at low frequency, ω is the angular frequency, τ is the relaxation time and F is a constant. The effect of adding Ethane or Propane shifts this relaxation time to a new relaxation time τ'. The shift in the relaxation time for small additions of ethane is proportional to the Ethane content of the mixture. The attenuation due to this new relaxation time τ' is thus given by:-

$$\alpha' = \frac{\omega}{4.c_0} . \frac{(\gamma_0 - 1)^2}{\gamma_0} . \frac{\omega.\tau'.F}{1 + (\omega.\tau')^2} \tag{4}$$

and the ratio of the measured pressure spectral responses is given by:-

$$\frac{p'(\omega)}{p(\omega)} = e^{-(\alpha' - \alpha)x} \tag{5}$$

where x is the distance between the transducers and $(\alpha'-\alpha)$ is given by :-

$$(\alpha' - \alpha) = \frac{\omega}{4.c_0} . \frac{(\gamma_0 - 1)^2}{\gamma} . \omega.F \left(\frac{\tau'}{1 + (\omega\tau')^2} - \frac{\tau}{1 + (\omega\tau)^2} \right) \tag{6}$$

The effect of this on the relative spectral response is shown in Figure 6, where the spectral response, relative to pure methane are plotted out for Methane for 2% and 6% Ethane. These clearly show the significant increase in transmission at low frequencies through the mixtures over than that through pure Methane. It is this increase which it is believed gives rise to the relatively large change in received amplitude when small amounts of Ethane are added.
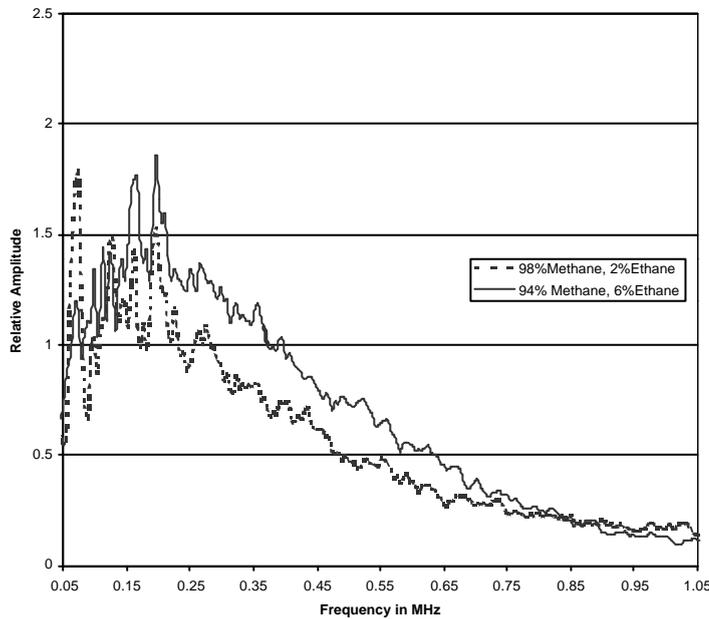

Figure 6: Relative amplitude responses for 2% and 6% addition of Ethane to Methane

6.   CONCLUSIONS

The work undertaken to date has demonstrated that in a mixture of three hydrocarbon gases, Methane, Ethane, and Propane it is possible to determine the relative proportions of the three gases at low levels of Ethane and Methane to an accuracy of $\pm0.5\%$. It has been shown that potentially the method offers scope for measuring the calorific value or density of the mixture purely from ultrasonic measurements. Further work is currently being undertaken to examine the effects of other gases such

as Nitrogen and Carbon Dioxide on this measurement technique and also the effect of ambient temperature and pressure.

7.   ACKNOWLEDGEMENTS

8.   REFERENCES

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